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BULK DEPOSITION IN THE SUDBURY AND MUSKOKA-HALIBURTON  
AREAS OF ONTARIO DURING THE SHUTDOWN OF INCO LTD. IN  
SUDBURY, 1980.

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BULK DEPOSITION IN THE SUDBURY AND  
MUSKOKA - HALIBURTON AREAS OF ONTARIO  
DURING THE SHUTDOWN OF  
INCO LTD. IN SUDBURY

by

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## Abstract

The shutdown of the Inco Ltd. smelter in Sudbury between September 1978 and June 1979 allowed us to evaluate its contribution to the bulk deposition (defined as the precipitation caught in a continuously open collector including wet and dry fallout) of free hydrogen ion, sulphate, total copper and total nickel at eight sites near Sudbury and at eight sites in Muskoka-Haliburton. Bulk depositions of total copper and total nickel up to 50 km from Sudbury were significantly lower when Inco was not operating. The deposition of sulphate decreased significantly at sites within 12 km of Sudbury during the shutdown, but there was no corresponding decrease in free hydrogen ion. There were no significant decreases in the deposition of sulphate, free hydrogen ion or total copper at Muskoka-Haliburton during the shutdown. Total nickel levels at Muskoka-Haliburton were commonly below the detection limit of the analytical method employed both before and during the shutdown.



## Introduction

It is well recognized that the deposition of strong acids and heavy metals from the atmosphere has affected the chemistry and biota of lakes in the greater Sudbury area (Conroy et al. 1975, Beamish 1976, Dillon et al. 1979). The source of the acidic material and heavy metals has commonly been attributed to the smelting industries in Sudbury because of the amount of material they emit and their proximity to the affected lakes. In fact, the nickel smelting industries in Sudbury have emitted between  $1.5$  and  $2.7 \times 10^6$  m.t. of  $\text{SO}_2$   $\text{yr}^{-1}$  for a minimum of 25 years, with emissions from a single 381 m. stack (Inco Ltd.) representing the largest point source of  $\text{SO}_2$  in the world (Summers and Whelpdale 1976). Emissions in the mid 1970's of Cu and Ni from major sources in the Sudbury area were estimated to be 1100 m.t.  $\text{yr}^{-1}$  each (Air Resources Branch, Ontario Ministry of the Environment).

A unique opportunity to study the effects of the Inco operations on the deposition of these substances in the Sudbury area was presented when the company was completely shut down by a strike between the fall of 1978 and spring of 1979. This shutdown resulted in an estimated decrease of 84, 69 and 58% in  $\text{SO}_2$ , copper and nickel emissions respectively in the Sudbury area. Before and during this time period, we measured bulk deposition using eight collectors at three sites near Sudbury and eight collectors in the Muskoka-Haliburton area, 225 km southeast of Sudbury, as part of our investigations of the mass budgets of a number of substances for both lakes and watersheds (Scheider et al. 1979, Jeffries and Snyder in press). In this paper, we address the question of the present effect of the Inco operations on the free hydrogen ion ( $\text{H}_f^+$ ), sulphate ( $\text{SO}_4^{2-}$ ), total Cu (t-Cu) and total Ni (t-Ni) deposition in the Sudbury area through a comparison of bulk deposition data collected before and during the period Inco was not operating. However, we can make no statement about historical sources of acid and metal contamination of the lakes and streams in the Sudbury area based on these data.

## Methods

The data presented in this paper were obtained from collections of bulk deposition unless otherwise noted. We define bulk deposition as the precipitation caught in a continuously open collector, which includes wet fallout (rain, snow) and an unknown fraction of the dry component of fallout (particulate material, aerosols and gases). Collector locations are shown in Fig. 1. The type of collectors used, frequencies of sample collection



and analytical methods, as well as techniques to measure rain and snowfall depths are discussed elsewhere (Scheider et al. 1979, Jeffries and Snyder in press).

The Inco Ltd. smelters in Sudbury were not operated between July 17, 1978 and August 27, 1978, or between September 15, 1978 and June 4, 1979. The smaller Falconbridge smelter was shut down between July 1, 1978 and August 21, 1978. Since Inco operated for part of July, August and September, 1978, for the purposes of this report we have considered the shutdown period to begin on October 1, 1978. Data collected to the end of April, 1979 are included. Because there were seasonal trends in bulk deposition of  $\text{SO}_4^{2-}$ , t-Cu and t-Ni (although not  $\text{H}_f^+$ ), it was necessary to compare pre- and post shutdown data collected over the same portion of the year.

At Muskoka-Haliburton (MH), collection of bulk precipitation began in July 1976, but analyses of t-Cu and t-Ni were not performed until October 1977. Nickel depositions at MH were frequently less than the detection limit ( $2 \mu\text{g L}^{-1}$ ) of the analytical procedure employed. There were eight bulk collectors at MH over the study period (Fig. 2), but no one collector provided a continuous record due to sampler malfunction, sample breakage, contamination or analytical error. We therefore employed two-way analysis of variance (ANOVA) (Snedecor and Cochran 1967) and Tukey's t-test (Tukey 1949) using collectors as replicates and monthly deposition as treatments to determine if the data from the different collectors could be pooled to give one complete, composite record of bulk deposition for MH.

Prior to statistical analysis, the depth and deposition data were log-transformed (Kramer 1976). Jeffries et al. (1978) have previously suggested that deposition of  $\text{H}_f^+$  and  $\text{SO}_4^{2-}$  at MH during summer months was normally distributed. Hence statistical analyses were carried out for these two parameters on both transformed and untransformed data. Statistical analyses were performed at the  $p=0.05$  level of significance unless otherwise noted.

The results indicated that, prior to shutdown, there was significant variation between months but not between collectors for depth and t-Cu deposition. The variation in the deposition of  $\text{H}_f^+$  and  $\text{SO}_4^{2-}$  was greater between months ( $p = 0.001$ ) than between collectors ( $p = 0.05$  or  $p = 0.01$ ) using both log-transformed and non-transformed data. During the period of shutdown, there was significant variation in depth and in the deposition of



$H_f^+$  and  $SO_4^{2-}$  between months but not between collectors. The deposition of t-Cu did not vary significantly between either months or collectors. The ANOVA technique was not used for t-Ni because concentrations were frequently less than the detection limit.

In light of the above findings, and because it was essential to obtain a complete record of bulk deposition, we pooled the data from collectors within the MH station. To do this, daily bulk deposition rates (total deposition per collection period/number of days per period) were calculated for each collector. An arithmetic mean daily deposition was obtained for each day by averaging the daily rates for all collectors operating within the station on that day. The daily values were summed to give the monthly bulk deposition. Monthly depth of precipitation was calculated in the same manner.

At Sudbury, deposition measurements using eight bulk collectors were initiated in January 1976 (Fig. 2). As at Muskoka-Haliburton, no single collector provided a complete, continuous record of deposition. Because the deposition of some substances emitted by tall stacks may decrease exponentially with distance from the source (Rodhe and Grandell 1972), and because the Sudbury smelting operations result in low altitude or fugitive emissions that may be deposited near their source, we used ANOVA and Tukey's t-test to determine if bulk deposition data from all collectors could be pooled. Enough data for statistical analysis existed at five of the eight collectors prior to shutdown (Hannah, Middle, Clearwater, Lohi, Nelson). Test results showed that there was significant variation between months but not between collectors for depth,  $H_f^+$  and  $SO_4^{2-}$  (log-transformed and non-transformed). However, significant differences in the deposition of t-Cu and t-Ni between collectors suggested pooling data into three stations: Sudbury North (SN), consisting of Nelson, Mountaintop, Tower and Joe collectors 30 - 50 km north of the point source; Sudbury South (SS), consisting of Lohi and Clearwater collectors 10 - 12 km south of the point source; and Sudbury Center (SC), consisting of Hannah and Middle collectors 4 - 5 km south of the point source.

ANOVA and Tukey's t-test were subsequently applied to data from collectors within each station grouping. For SN prior to shutdown, only Nelson and Mountaintop collectors had sufficient data for statistical analysis. Results showed that, except for t-Cu, the variation between collectors was not significant. The variation between collectors and months was significant at  $p = 0.025$  for t-Cu. During the period of shutdown, insufficient data precluded testing the comparability of the collectors. Although unable to test



the comparability of the other two collectors (Tower and Joe) near Nelson, we have combined all four collectors into the Sudbury North (SN) station.

Prior to shutdown, the application of ANOVA and Tukey's t-test to data from collectors within the SS and SC stations showed that there was no significant variation in depth or deposition between collectors within each station, with the exception of t-Ni for SS. In this case, the variation between months was greater ( $p = 0.001$ ) than that between collectors ( $p = 0.005$ ). During the shutdown, test results showed there was no significant variation between collectors within stations, with the exception of depth for SC. The variation between months ( $p = 0.001$ ) was greater than that between collectors ( $p = 0.005$ ) in this case. Based on the above results, and because it was essential to have a complete record of bulk deposition, we combined data from the collectors to form the SS and SC stations. Monthly depth and deposition data were calculated in the same manner as for the MH station.

To test whether the deposition of  $H_f^+$ ,  $SO_4^{2-}$ , total Cu and total Ni were reduced at the four stations during the period Inco was not operating relative to the pre-shutdown period, we carried out a t-test on log-transformed data paired by month (Snedecor and Cochran 1967). However, as our data sets were too limited to rigorously test the assumption of a log-normal distribution, we also used a Wilcoxon rank sum test (Snedecor and Cochran 1967), the non-parametric version of the paired t-test. For both tests, data from the periods October 1976 - April 1977, October 1977 - April 1978, and October 1978 - April 1979 (the latter being the shutdown period during which Inco was not operating) were used. Thus, two seven-month control periods with Inco in operation and one seven-month period during shutdown were employed.

For each of the four stations and for each of  $H_f^+$ ,  $SO_4^{2-}$ , total Cu and total Ni, null and alternate hypotheses were set as follows, based on the expectation that depositions during the shutdown period would be lower than those during the period Inco was in operation.

| <u>Null Hypothesis</u>                                                      | <u>Alternate Hypothesis</u>                                                      |
|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| deposition in Oct. 1976 - April 1977 = deposition in Oct. 1977 - April 1978 | deposition in Oct. 1976 - April 1977 $\neq$ deposition in Oct. 1977 - April 1978 |
| deposition in Oct. 1976 - April 1977 = deposition in Oct. 1978 - April 1979 | deposition in Oct. 1976 - April 1977 $>$ deposition in Oct. 1978 - April 1979    |
| deposition in Oct. 1977 - April 1978 = deposition in Oct. 1978 - April 1979 | deposition in Oct. 1977 - April 1978 $>$ deposition in Oct. 1978 - April 1979    |



Using Muskoka-Haliburton as a control site, another set of null and alternate hypotheses was set up for each parameter and each of the three October - April periods. Based on the expectation that the deposition would be greater near Sudbury than in Muskoka-Haliburton, the hypotheses are as follows:

| <u>Null Hypothesis</u>                 | <u>Alternate Hypothesis</u>            |
|----------------------------------------|----------------------------------------|
| deposition at MH =<br>deposition at SN | deposition at SN ><br>deposition at MH |
| deposition at MH =<br>deposition at SS | deposition at SS ><br>deposition at MH |
| deposition at MH =<br>deposition at SC | deposition at SC ><br>deposition at MH |

## Results

Monthly depositions of  $H_f^+$ ,  $SO_4^{2-}$ , t-Cu and t-Ni and depth of precipitation, shown in Fig. 3 - 7 respectively, demonstrate the large temporal variability of the data. Seasonal patterns of deposition for  $SO_4^{2-}$ , t-Cu and t-Ni are evident for most stations, but trends for  $H_f^+$  deposition are unclear. The plots demonstrate the dramatic decrease of t-Cu and t-Ni deposition at the Sudbury stations during the period Inco was shut down. Total deposition of  $H_f^+$ ,  $SO_4^{2-}$ , t-Cu and t-Ni and depth of precipitation for the periods October 1977 - April 1978 (operating), and October 1978 - April 1979 (shutdown), are summarized in Table 1. In the October 1976 - April 1977 period, data were missing for some months for each variable, precluding comparison of the total deposition for equivalent seven-month periods. Although the depositions of t-Ni at MH were frequently less than the detection limit of the analytical method employed, we assumed  $[t-Ni] = \text{detection limit}$  for the purposes of calculations summarized in Tables 1 and 2, and Fig. 6.

The most striking change evident in Table 1 is the 3 - 76 fold decrease of t-Cu and t-Ni depositions in the shutdown period compared to the operating period at the Sudbury stations. In contrast, deposition of t-Cu increased during shutdown at MH. The deposition of  $H_f^+$  also increased during shutdown at MH, SN and SS, but decreased at SC. For  $SO_4^{2-}$ , deposition during shutdown increased at MH, decreased at SS and SC (equivalent six-month periods) and remained unchanged at SN. More precipitation fell during the shutdown period than fell during the operating period, the greatest increase occurring at the MH station.



In order to statistically compare the depositions before and during the shutdown, we carried out paired t-tests on log-transformed data and Wilcoxon rank sum tests (the latter was used only if the number of months with data  $\geq 5$ ). The results of these tests are summarized in Table 2. Because the paired t-test is a more powerful test, results were frequently significant at a lower p level than results of the Wilcoxon test. However, with the exception of four cases (in 51), both tests indicated that the same conclusion could be drawn at a significance level  $p = 0.05$ . In three of the four cases where conclusions were apparently different, one result was significant at  $p \leq 0.05$  while the other was significant at  $p = 0.10$ , and we rejected the null hypothesis. In the remaining case, we did not reject the null hypothesis. In testing to determine if the depositions of  $H_f^+$ ,  $SO_4^{2-}$ , total Cu and total Ni were greater during the period Inco was operating, results of the tests had to demonstrate (at  $p = 0.05$  unless noted) both (i) that there was no significant difference in depositions between the two operating periods, and (ii) that depositions in both operating periods were higher than the deposition in the shutdown period. If these conditions were met, the null hypothesis was rejected and the alternate hypothesis that bulk deposition changed significantly during the period Inco was not operating was accepted.

There was no significant difference (Table 2) in  $H_f^+$  deposition either between the two operating periods or between the operating and shutdown periods at the SN, SS or SC stations. At MH,  $H_f^+$  deposition was not significantly different between operating periods and was actually higher during the shutdown compared to the pre-shutdown periods. Test results were the same for  $SO_4^{2-}$  as for  $H_f^+$  at MH. There was no significant difference in the deposition of  $SO_4^{2-}$  between any of the periods at SN. At SS, no significant differences were noted in the  $SO_4^{2-}$  deposition between the two operating periods, and only during one of the two seven-month operating periods (October 1976 - April 1977) was  $SO_4^{2-}$  deposition significantly greater than that during the shutdown period. However, at SC,  $SO_4^{2-}$  deposition during both periods when Inco was in operation was significantly greater than deposition during the shutdown.

At all three Sudbury stations, the deposition of t-Cu was significantly greater during the operating period than during the shutdown period. However, at SS, t-Cu deposition was also significantly different between the two operating periods, thereby clouding the interpretation of the results. There was no significant difference in t-Cu deposition at MH between the operating



periods, and\* depositions during shutdown were higher than those during the pre-shutdown period.

Total Ni depositions at SS and SC were significantly greater during both operating periods than during shutdown. At SN, t-Ni deposition was significantly greater during the operating period October 1977 - April 1978 compared to that measured during shutdown. Although there was no significant difference in t-Ni deposition between the other operating period and the shutdown period, the number of months tested was small ( $n = 2$ ). Total Ni deposition was not significantly different between any periods at the MH station.

Another set of null hypotheses treated MH as a control station, with the expectation that the depositions of  $H_f^+$ ,  $SO_4^{2-}$ , t-Cu and t-Ni at the Sudbury stations would be greater than those at MH during the operating period but not different during the shutdown period. To accept this hypothesis, the results of the tests had to demonstrate (at  $p = 0.05$  unless noted) both that (i) the deposition at the Sudbury station was greater than the deposition at MH in both operating periods, and (ii) that the deposition at the Sudbury station was either less than or equal to the deposition at MH during shutdown.

There was no significant difference in  $H_f^+$  deposition during either operating period comparing MH to the SS and SC stations. The deposition of  $H_f^+$  at the SN station was significantly greater than that at MH during one of two operating periods (October 1976 - April 1977). During the shutdown, the  $H_f^+$  deposition was significantly different (greater) at MH than at the Sudbury stations. The deposition of  $SO_4^{2-}$  was significantly greater at SS and SC than at MH prior to shutdown, but there was no significant difference during shutdown. At SN,  $SO_4^{2-}$  deposition was not significantly different than at MH, either before or during shutdown.

For t-Cu, the depositions at all Sudbury stations prior to shutdown were significantly greater ( $p = 0.10$  for SN-MH October 1976 - April 1977, with  $n = 2$ ) than those measured at MH prior to shutdown. During shutdown, t-Cu depositions were either not significantly different at the Sudbury stations vs. MH or were actually lower at Sudbury than at MH. The depositions of t-Ni at the Sudbury stations were significantly greater (except SN-MH October 1976 - April 1977 with  $n = 2$ ) than those at MH prior to shutdown. During shutdown, t-Ni depositions at Sudbury were either less than or not significantly different from those at MH.



The results of ANOVA and Tukey's t-test on log-transformed depositions for the Hannah, Middle, Clearwater, Lohi and Nelson collectors during shutdown were different from those found during the earlier operating period. Whereas prior to the shutdown the collectors had to be separated into three stations (i.e.: SN, SS and SC) based on the t-Cu and t-Ni levels, during the shutdown there was no significant difference in  $H_f^+$ ,  $SO_4^{2-}$ , t-Cu or t-Ni depositions between any of the five collectors.

T-tests on precipitation depths (log-transformed) paired by month and Wilcoxon tests were performed to assess whether significant ( $p = 0.05$ ) differences in depth occurred between periods when Inco was operating or not operating. Another set of tests was performed comparing depths at the control station, MH, to those measured at the Sudbury stations over equivalent time periods. Depth data from the same pairs of stations and periods as summarized in Table 2 were tested. In the period October 1976 - April 1977, significantly more precipitation fell at SN than at MH (although  $n = 2$ ). There was significantly more precipitation in the shutdown period than in either operating periods at MH. Differences between precipitation depths were not significant between any other periods or stations. These tests confirm that differences observed in depositions between operating and shutdown periods and between Sudbury stations and MH were not merely due to differences in the amount of precipitation.

## Discussion

The shutdown of the Inco Ltd. smelting operations at Sudbury between September 1978 and June 1979 has allowed us to assess their current contribution to bulk deposition, both at Sudbury and in Muskoka-Haliburton. However, based on this information, we cannot comment on either the historical causes of the acidification of lakes and watersheds in the Sudbury area or the relative importance of the different components of the smelting operations (e.g.: emissions from the 381 m stack, fugitive emissions) to the bulk deposition.

The results of the paired t-test and Wilcoxon test showed that during the period Inco was not operating there was no significant decrease in the deposition of  $H_f^+$ ,  $SO_4^{2-}$ , total Cu or total Ni at Muskoka-Haliburton. In fact, the depositions of  $H_f^+$ ,  $SO_4^{2-}$  and t-Cu were significantly greater in the shutdown period than in both pre-shutdown periods. Studies of storm tracks (Summers and Whelpdale 1976, Whelpdale 1978, Kurtz and Scheider 1980) show that most of the  $H_f^+$  and  $SO_4^{2-}$  deposited in southern



Ontario is associated with southerly air flows. In the light of these results, the lack of a significant decrease in  $H_f^+$ ,  $SO_4^{2-}$  and t-Cu in the bulk deposition at the MH station is not surprising.

The  $H_f^+$  deposition showed no significant decrease at any of the Sudbury stations during the period of Inco shutdown. However, these results should be viewed in the light of those at Muskoka-Haliburton. The  $H_f^+$  deposition at MH was higher during the shutdown than during the two preceding pre-shutdown periods. If we assume that the same pattern of long range transport affects Sudbury as affects Muskoka-Haliburton, then we might also expect the  $H_f^+$  deposition to have increased at the Sudbury stations as it did at the MH station, because of a larger input from long range transport. The validity of this assumption is unknown, but reports in Ontario (Summers and Whelpdale 1976, Whelpdale 1978, Kurtz and Scheider 1980) and the northeastern U.S.A. (Cogbill and Likens 1974, Dittenhoeffer and Dethier 1976, Miller et al. 1978) note that most of the acidic precipitation is associated with air flows from the south and southwest. This suggests that although they are 225 km apart, the Sudbury and MH stations would be affected by the same regional air masses. The fact that  $H_f^+$  deposition did not change during shutdown at the Sudbury stations but increased at the MH station suggests that there is a possibility that a decreased input of  $H_f^+$  to precipitation from Inco was countered by an increased  $H_f^+$  input to precipitation from long range transport.

The  $SO_4^{2-}$  deposition at the SN station prior to shutdown was not significantly different than that during the shutdown period, nor was it significantly different than that at the MH station. These results suggest that the Inco operations had little effect on  $SO_4^{2-}$  deposition at this station. However,  $SO_4^{2-}$  deposition was significantly greater at SS and SC than at MH prior to shutdown, but no different during shutdown. This, plus the fact that  $SO_4^{2-}$  deposition decreased significantly at these stations when Inco was not operating (except at SS, comparing October 1977 - April 1978 to the shutdown period), argues for the hypothesis that Inco is elevating bulk deposition of  $SO_4^{2-}$  in the immediate Sudbury area. Kramer (1975) reported elevated bulk  $SO_4^{2-}$  deposition at collectors near Sudbury compared to those in other parts of northern Ontario and also reported (Kramer 1973) a decrease in  $SO_4^{2-}$  deposition up to 50 miles from Sudbury during the brief period (August 1972 - September 1972) when both Inco and Falconbridge shut down their smelters.

The different conclusions reported here for  $SO_4^{2-}$  relative to  $H_f^+$  indicate that the acidity of precipitation cannot be inferred from the  $SO_4^{2-}$  levels alone. The nitrogen oxides, ammonium ion and, near Sudbury, heavy metal



content of bulk precipitation probably all play important roles in determining its acidity.

There was a significant decrease in t-Cu and t-Ni depositions at all Sudbury stations during the period Inco was not in operation. In fact, depositions decreased to levels that were either not significantly different from or actually lower than those measured at Muskoka-Haliburton. Jeffries and Snyder (in press) have shown that bulk t-Cu and t-Ni depositions at the Sudbury stations are at the high end of the range reported for urban-industrial environments. Kramer (1975) presented data showing elliptical contour maps of bulk t-Cu and t-Ni depositions with the highest values centered in Sudbury. Our results demonstrate clearly that the Inco operations are the reason that the t-Cu and t-Ni depositions are currently elevated in the Sudbury area. Kramer (1973) also found the bulk deposition of t-Cu and t-Ni decreased by about tenfold during the shutdown period of August 1972 - September 1972.

The measured decreases in t-Cu and t-Ni depositions partially reflect the locations of the collectors. No collectors were situated as close to the Falconbridge smelter, which operated throughout the October 1978 - April 1979 period, as SC and SS were to the Inco smelters. At our stations, particularly SC, fugitive emissions of t-Cu and t-Ni, as well as of  $\text{SO}_4^{2-}$ , probably contributed to the bulk deposition. This hypothesis is supported by a comparison of bulk and wet-only deposition during operating periods.

Jeffries and Snyder (in press) have shown that for t-Cu, the percent of dry fallout (calculated as bulk minus wet deposition) present in bulk deposition was 72% and 47% for SN and SC stations respectively during the period May - October 1977. Similarly, 11% and 43% of the t-Ni present in bulk deposition at SN and SC was deposited by dry processes. The fraction of bulk deposition that falls in the dry form would probably be lower in the October - April period because of the reduced amounts of dust, pollen, etc. in the winter period. Although these figures are only approximations (probably underestimates) of the dry deposition, they do suggest that a considerable portion of the t-Cu and t-Ni fallout in Sudbury is due to the dry component of bulk precipitation. In comparison, all of the t-Cu deposited at MH (Oct. 1977 - Sept. 1978) could be attributed to wet depositional processes (Jeffries and Snyder, in press).

Our conclusions regarding the elevation of  $\text{SO}_4^{2-}$ , t-Cu and t-Ni depositions in the Sudbury area are supported by the results of other studies. Conroy et al. (1976) and Ontario Ministry of the Environment (1978) in surveys of 150 and 209 lakes respectively within a 200 km radius of Sudbury, found elevated



levels of  $\text{SO}_4^{2-}$ , t-Cu and t-Ni in a large area centered at Sudbury. In these same studies, elevated levels of t-Cu and t-Ni were found in the surficial sediments of lakes in an area again with Sudbury at its center. These results, combined with the bulk deposition findings reported in this paper, indicate that Sudbury, particularly Inco, is currently the major contributor of t-Cu and t-Ni to the lakes and watersheds of the study area. The fact that Inco also contributes to the long range transport of pollutants and ultimately to the regional problem of acidic precipitation is understood.

Conclusions: i) the bulk deposition of  $\text{H}_f^+$ ,  $\text{SO}_4^{2-}$  and t-Cu measured at Muskoka-Haliburton did not significantly decrease during the period Inco was not operating. This supports previous findings that levels of these ions in precipitation are governed by the long range transport of pollutants originating from many sources.

ii) the bulk deposition of  $\text{SO}_4^{2-}$  is elevated in the Sudbury area compared to Muskoka-Haliburton. Results demonstrated that  $\text{SO}_4^{2-}$  deposition decreased significantly during the Inco shutdown period, implying that Inco is a major contributor to elevated  $\text{SO}_4^{2-}$  deposition to distances of at least 12 km from Sudbury.

iii) the t-Cu and t-Ni depositions in Sudbury are among the highest recorded in the world. Results showed that the t-Cu deposition and t-Ni deposition in the Sudbury area decreased by almost two orders of magnitude during the period of Inco shutdown. The resulting levels were no higher than those measured at Muskoka-Haliburton. These results imply that Inco is a major contributor of Cu and Ni to bulk deposition to distances of at least 50 km from Sudbury.



## References

- Beamish, R. J. (1976). Acidification of lakes in Canada by acid precipitation and resulting effects on fishes. *Water, Air and Soil Pollution* 6, 501-514.
- Cogbill, C. V. and Likens, G. E. (1974). Acid precipitation in the north-eastern United States. *Water Resour. Res.* 10, 1133-1137.
- Conroy, N., Hawley, K., Keller W. and Lafrance, C. (1975). Influences of the atmosphere on lakes in the Sudbury area. *Proc. First Spec. Symp. on atmospheric contributions to the chemistry of lakewaters. J. Int. Assoc. Great Lakes Res.* 2, 146-155.
- Dillon, P. J., Yan, N. D., Scheider, W. A. and Conroy, N. (1979). Acidic lakes in Ontario, Canada: characterization, extent and responses to base and nutrient additions. *Arch. Hydrobiol. Beih. Ergebn. Limnol.* 13, 317-336.
- Dittenhoefer, A. C. and Dethier, B. E. (1976). The precipitation chemistry of western New York state: a meteorological interpretation. Office of Water Research and Technology, U. S. Dept. of the Interior.
- Jeffries, D. J. and Snyder, W. R. (in press). Concentration and deposition of heavy metals in precipitation in central Ontario. *Water, Air and Soil Pollution*.
- Jeffries, D. S., Snyder, W. R., Scheider, W. A. and Kirby, M. (1978). Small-scale variations in precipitation loading near Dorset, Ontario. *Water Poll. Res. Canada.* 13, 73-84.
- Kramer, J. R. (1973). Atmospheric composition and precipitation of the Sudbury region. *Alternatives* 2, 18-25.
- Kramer, J. R. (1975). Fate of atmospheric sulphur dioxide and related substances as indicated by chemistry of precipitation. McMaster University. 92p.
- Kramer, J. R. (1976). Fate of atmospheric sulphur dioxide and related substances as indicated by chemistry of precipitation. McMaster University. 67p.
- Kurtz, J. and Scheider, W. A. (1980). Acidic precipitation in south-central Ontario: analysis of source regions using air parcel trajectories. Ontario Ministry of the Environment. 20p.
- Miller, J. M., Galloway, J. N. and Likens, G. E. (1978). Origin of air masses producing acid precipitation at Ithaca, New York. *Geophysical Research Letters* 5, 757-760.



- Ontario Ministry of the Environment (1978). Extensive monitoring of lakes in the greater Sudbury area 1974-1976. Ontario Ministry of the Environment. 40p.
- Rodhe, H. and Grandell, J. (1972). On the removal of aerosol particles from the atmosphere by precipitation scavenging. *Tellus* 24, 442-454.
- Scheider, W. A., Snyder, W. R. and Clark, B. (1979). Deposition of nutrients and major ions by precipitation in south-central Ontario. *Water, Air and Soil Pollution*. 12, 171-185.
- Snedecor, G. W. and Cochran, W. G. (1967). Statistical methods. The Iowa State University Press, Iowa. 593p.
- Summers, P. W. and Whelpdale, D. M. (1976). Acid precipitation in Canada. *Water, Air and Soil Pollution* 6, 447-455.
- Tukey, J. W. (1949). Comparing individual means in analysis of variance. *Biometrics* 5, 99-114.
- Whelpdale, D. M. (1978). Large-scale atmospheric sulphur studies in Canada. *Atmospheric Environment* 12, 661-670.



Table 1: Depth of precipitation and bulk deposition of  $H_f^+$ ,  $SO_4^{2-}$ , total Cu and total Ni at Muskoka-Haliburton, Sudbury North, Sudbury South and Sudbury Center, for the periods October 1977 - April 1978, and October 1978 - April 1979. n = number of months used in calculation.

| Ion                            | Site               | Oct. 1977-<br>Apr. 1978 | (n) | Oct. 1978-<br>Apr. 1979 | (n) |
|--------------------------------|--------------------|-------------------------|-----|-------------------------|-----|
| $H^+$<br>(meq $m^{-2}$ )       | Muskoka-Haliburton | 27.5                    | 7   | 56.3                    | 7   |
|                                | Sudbury - North    | 27.9                    | 7   | 34.7                    | 7   |
|                                | - South            | 27.9                    | 7   | 31.6                    | 7   |
|                                | - Center           | 34.2                    | 7   | 31.1                    | 7   |
| $SO_4^{2-}$<br>(meq $m^{-2}$ ) | Muskoka-Haliburton | 26.1                    | 7   | 37.2                    | 7   |
|                                | Sudbury - North    | 32.3                    | 7   | 32.4                    | 7   |
|                                | - South            | 28.4                    | 6   | 28.9                    | 7   |
|                                | - Center           | 39.5                    | 6   | 30.8                    | 7   |
| total Cu<br>(mg $m^{-2}$ )     | Muskoka-Haliburton | 0.95                    | 7   | 4.83                    | 7   |
|                                | Sudbury - North    | 20.5                    | 7   | 1.29                    | 7   |
|                                | - South            | 63.0                    | 7   | 2.09                    | 7   |
|                                | - Center           | 240                     | 7   | 3.15                    | 7   |
| total Ni<br>(mg $m^{-2}$ )     | Muskoka-Haliburton | < 0.60                  | 7   | < 2.02                  | 6   |
|                                | Sudbury - North    | 4.42                    | 7   | 1.27                    | 7   |
|                                | - South            | 74.9                    | 7   | 1.21                    | 7   |
|                                | - Center           | 91.7                    | 7   | 1.46                    | 7   |
| Depth<br>(mm)                  | Muskoka-Haliburton | 387.2                   | 7   | 548.6                   | 7   |
|                                | Sudbury - North    | 448.8                   | 7   | 549.6                   | 7   |
|                                | - South            | 415.6                   | 7   | 509.5                   | 7   |
|                                | - Center           | 422.2                   | 7   | 528.8                   | 7   |



Table 2: Comparison of bulk deposition of  $H_f^+$ ,  $SO_4^{2-}$ , total Cu and total Ni collected before and during the Inco shutdown period, using a paired t-test on log-transformed data and a Wilcoxon rank sum test. No = null hypothesis not rejected; alternate hypothesis accepted if  $p \leq 0.05$  (see text).

| Null hypothesis <sup>a</sup> | Alternate hypothesis | $H_f^+$            |   |                   | $SO_4^{2-}$        |   |               | total Cu           |   |                    | total Ni          |   |                   |
|------------------------------|----------------------|--------------------|---|-------------------|--------------------|---|---------------|--------------------|---|--------------------|-------------------|---|-------------------|
|                              |                      | t-test             | n | Wilcoxon test     | t-test             | n | Wilcoxon test | t-test             | n | Wilcoxon test      | t-test            | n | Wilcoxon test     |
| MH76-77 = MH77-78            | MH76-77 ≠ MH77-78    | no                 | 7 | no                | no                 | 6 | no            | no                 | 5 | no                 | no                | 5 | no                |
| MH76-77 = MH78-79            | MH76-77 > MH78-79    | no                 | 7 | no                | no                 | 6 | no            | no                 | 5 | no                 | no                | 4 | -                 |
| MH77-78 = MH78-79            | MH77-78 > MH78-79    | no                 | 7 | no                | no                 | 7 | no            | no                 | 7 | no                 | no                | 6 | no                |
| SN76-77 = SN77-78            | SN76-77 ≠ SN77-78    | no                 | 2 | -                 | no                 | 2 | -             | no                 | 2 | -                  | no                | 2 | -                 |
| SN76-77 = SN78-79            | SN76-77 > SN78-79    | 0.10               | 2 | -                 | 0.10               | 2 | -             | 0.025              | 2 | -                  | no                | 2 | -                 |
| SN77-78 = SN78-79            | SN77-78 > SN78-79    | no                 | 7 | no                | no                 | 7 | no            | 0.001              | 7 | 0.01               | 0.005             | 7 | 0.01              |
| SN76-77 = MH76-77            | SN76-77 > MH76-77    | 0.025              | 2 | -                 | no                 | 2 | -             | 0.010              | 2 | -                  | no                | 2 | -                 |
| SN77-78 = MH77-78            | SN77-78 > MH77-78    | no                 | 7 | no                | no                 | 7 | no            | 0.001              | 7 | 0.01               | 0.005             | 7 | 0.01              |
| SN78-79 = MH78-79            | SN78-79 ≠ MH78-79    | 0.05 <sup>b</sup>  | 7 | no                | no                 | 7 | no            | 0.005 <sup>b</sup> | 7 | 0.025 <sup>b</sup> | 0.10 <sup>b</sup> | 6 | no                |
| SS76-77 = SS77-78            | SS76-77 ≠ SS77-78    | no                 | 4 | -                 | no                 | 3 | -             | 0.01               | 5 | 0.10               | no                | 5 | no                |
| SS76-77 = SS78-79            | SS76-77 > SS78-79    | 0.10               | 4 | -                 | 0.005              | 4 | -             | 0.001              | 5 | 0.05               | 0.001             | 5 | 0.05              |
| SS77-78 = SS78-79            | SS77-78 > SS78-79    | no                 | 7 | no                | no                 | 6 | no            | 0.001              | 7 | 0.01               | 0.001             | 7 | 0.01              |
| SS76-77 = MH76-77            | SS76-77 > MH76-77    | no                 | 4 | -                 | 0.05               | 4 | -             | 0.001              | 3 | -                  | 0.001             | 3 | -                 |
| SS77-78 = MH77-78            | SS77-78 > MH77-78    | no                 | 7 | no                | 0.05               | 6 | 0.10          | 0.001              | 7 | 0.01               | 0.001             | 7 | 0.01              |
| SS78-79 = MH78-79            | SS78-79 ≠ MH78-79    | 0.025 <sup>c</sup> | 7 | 0.05 <sup>c</sup> | 0.10 <sup>c</sup>  | 7 | no            | 0.05 <sup>c</sup>  | 7 | 0.05 <sup>c</sup>  | 0.05 <sup>c</sup> | 6 | 0.10 <sup>c</sup> |
| SC76-77 = SC77-78            | SC76-77 ≠ SC77-78    | no                 | 4 | -                 | no                 | 4 | -             | no                 | 4 | -                  | no                | 4 | -                 |
| SC76-77 = SC78-79            | SC76-77 > SC78-79    | no                 | 4 | -                 | 0.005              | 4 | -             | 0.001              | 4 | -                  | 0.005             | 4 | -                 |
| SC77-78 = SC78-79            | SC77-78 > SC78-79    | no                 | 7 | no                | 0.005              | 6 | 0.025         | 0.001              | 7 | 0.01               | 0.001             | 7 | 0.01              |
| SC76-77 = MH76-77            | SC76-77 > MH76-77    | no                 | 4 | -                 | 0.05               | 3 | -             | 0.025              | 2 | -                  | 0.001             | 2 | -                 |
| SC77-78 = MH77-78            | SC77-78 > MH77-78    | 0.10               | 7 | no                | 0.025 <sup>d</sup> | 6 | 0.025         | 0.001              | 7 | 0.01               | 0.001             | 7 | 0.01              |
| SC78-79 = MH78-79            | SC78-79 ≠ MH78-79    | 0.025 <sup>d</sup> | 7 | 0.05 <sup>d</sup> | no                 | 7 | no            | no                 | 7 | no                 | no                | 6 | no                |

a. Legend: MH = Muskoka-Haliburton, SN = Sudbury North, SS = Sudbury South, SC = Sudbury Centre  
76-77 = time period October 1976 - April 1977 inclusive, 77-78 = time period October 1977 - April 1978 inclusive, 78-79 = time period October 1978 - April 1979 inclusive.  
For example: MH76-77 = MH77-78 means bulk deposition at the MH station in period Oct. 1976 - April 1977 equals the bulk deposition at the MH station in the period Oct. 1977 - April 1978.

b. MH > SN  
c. MH > SS  
d. MH > SC



### List of Figures

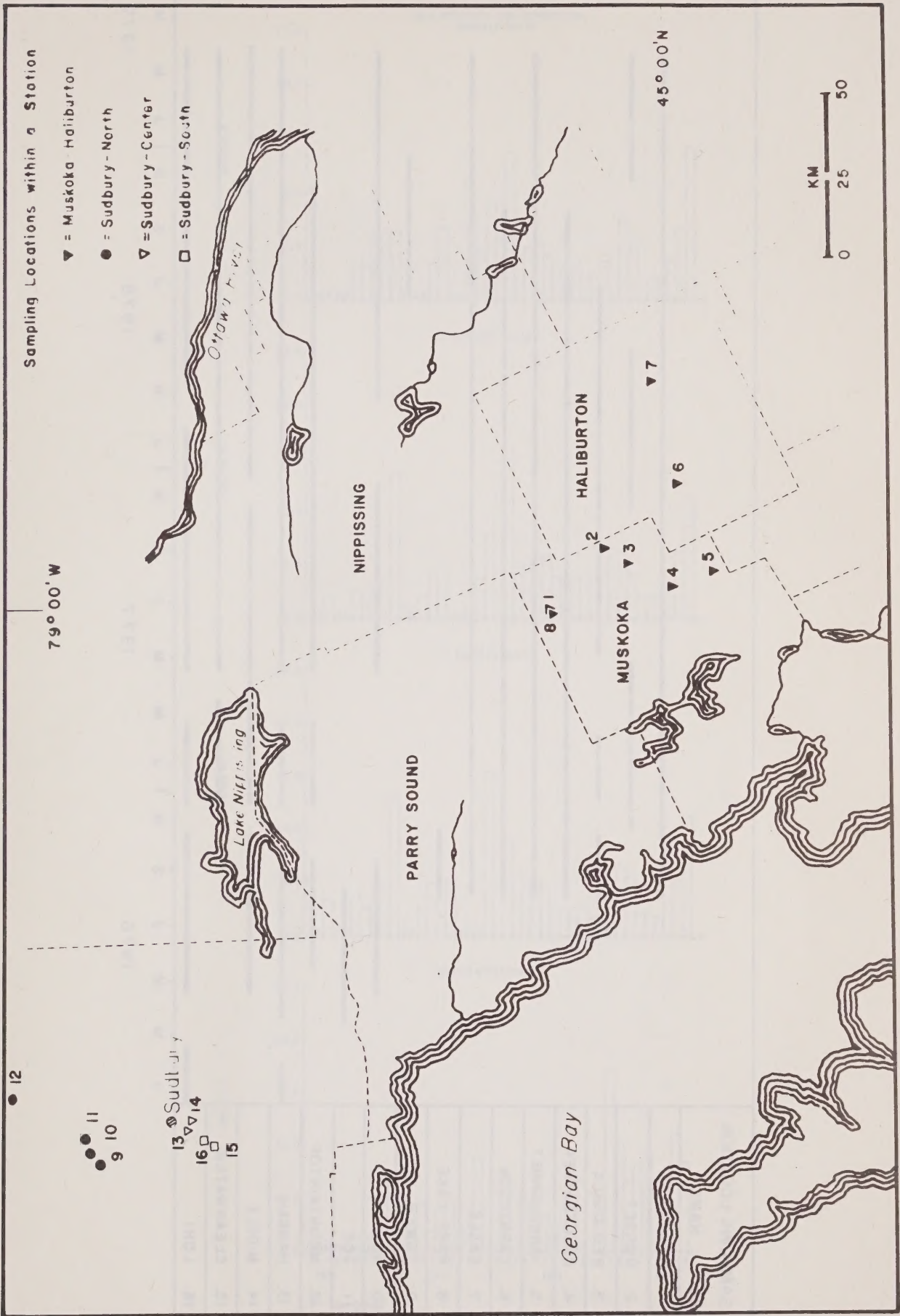
- Fig. 1. Location of precipitation collectors and station groupings. Collector numbers refer to those in Fig. 2.
- Fig. 2. Periods of operation for collectors within the Muskoka-Haliburton, Sudbury North, Sudbury South and Sudbury Center stations (see Fig. 1).
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- Fig. 7. Monthly precipitation depth in mm for Sudbury North, Sudbury Center, Sudbury South and Muskoka-Haliburton stations for January 1976 - April 1979. An asterisk indicates no data.



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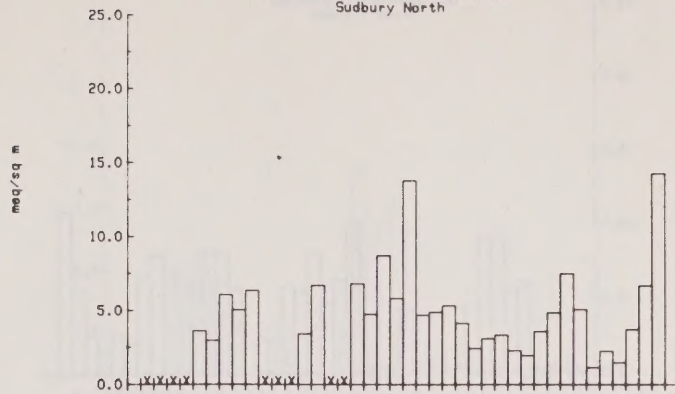




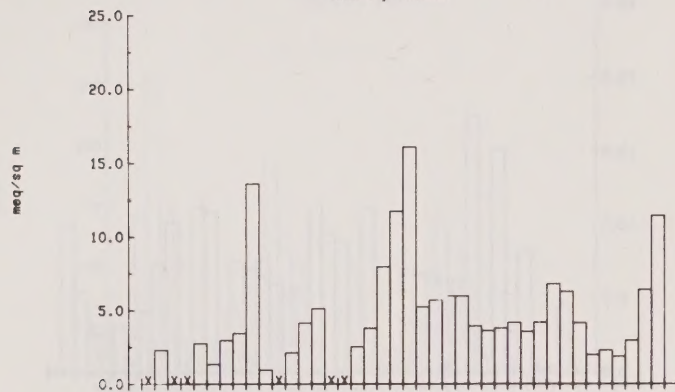
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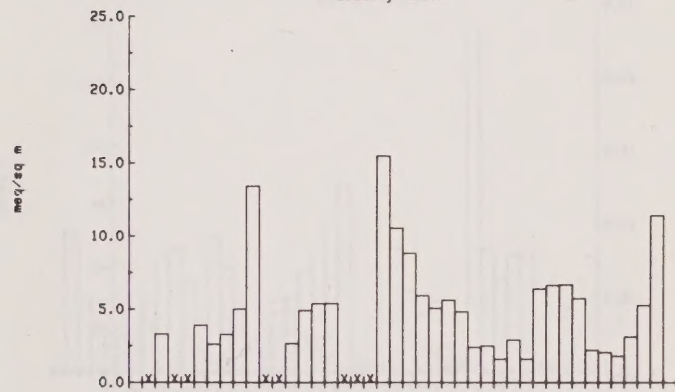
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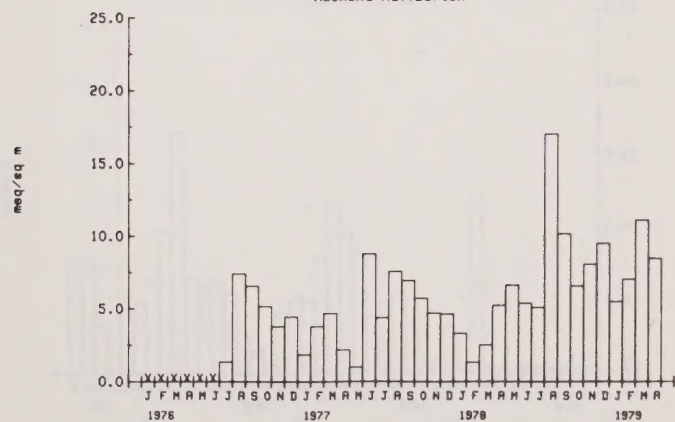
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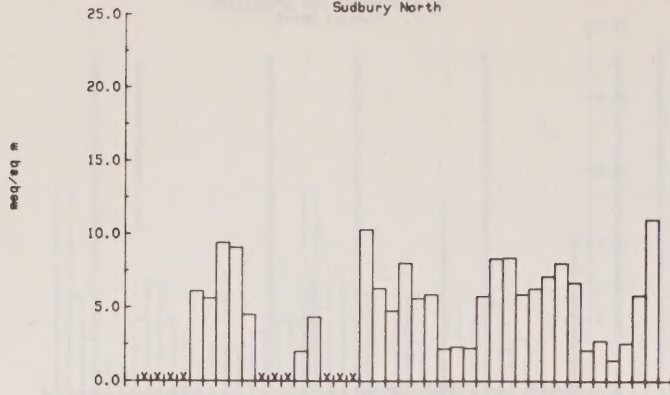


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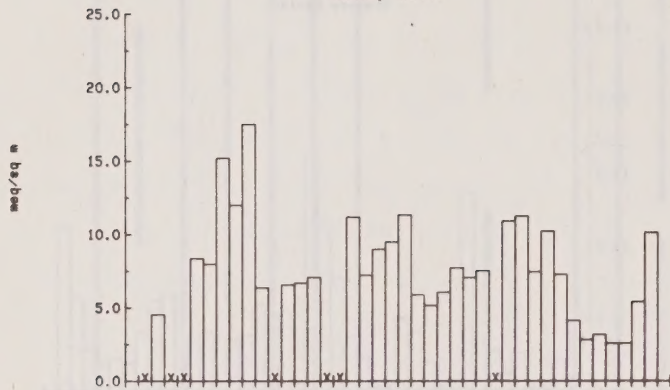


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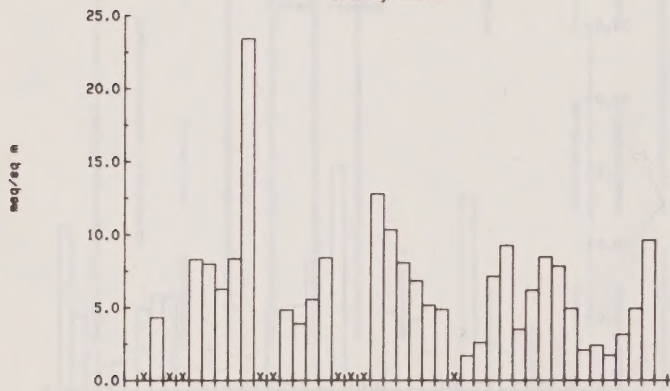
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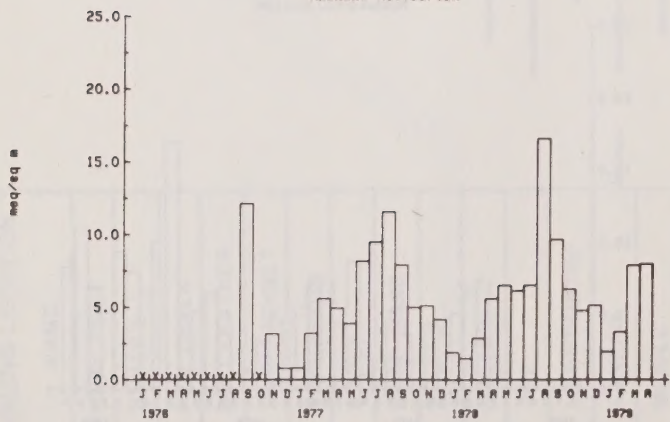
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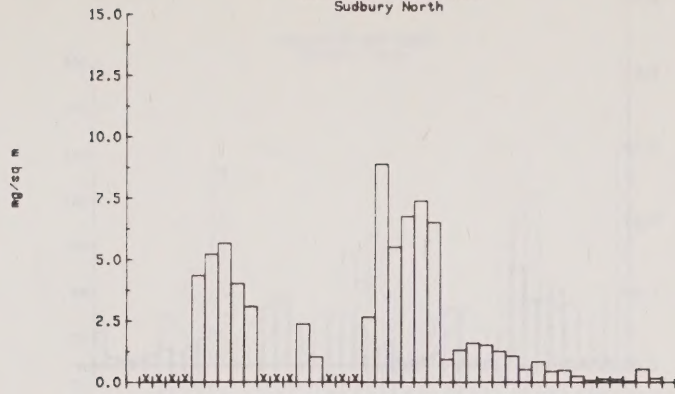
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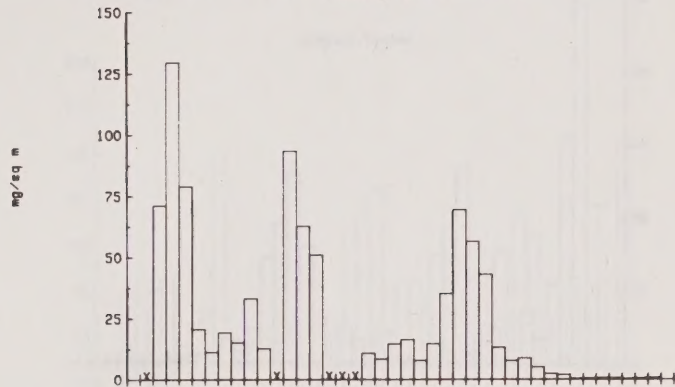
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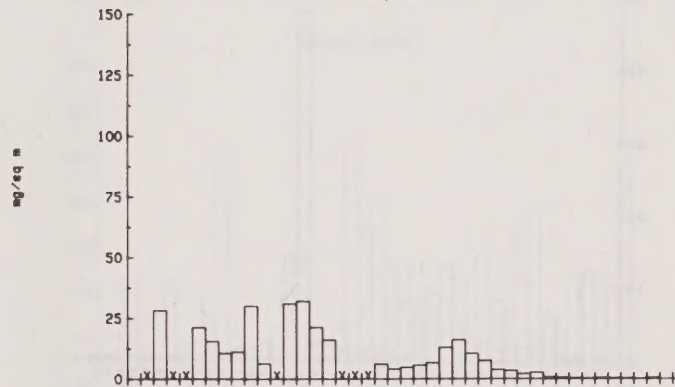
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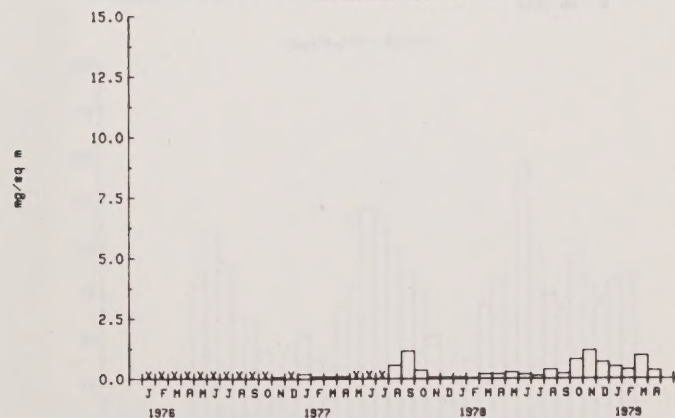
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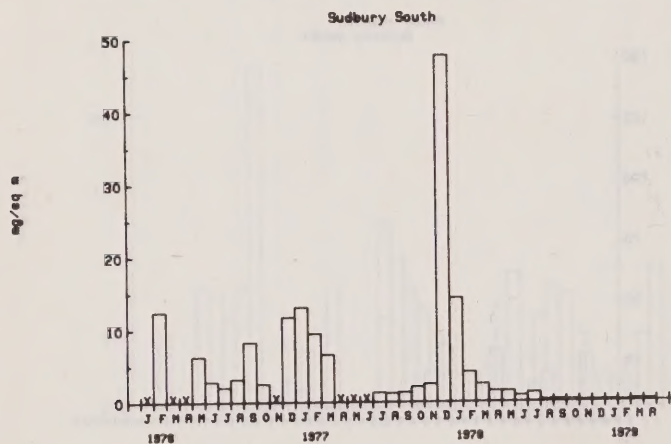
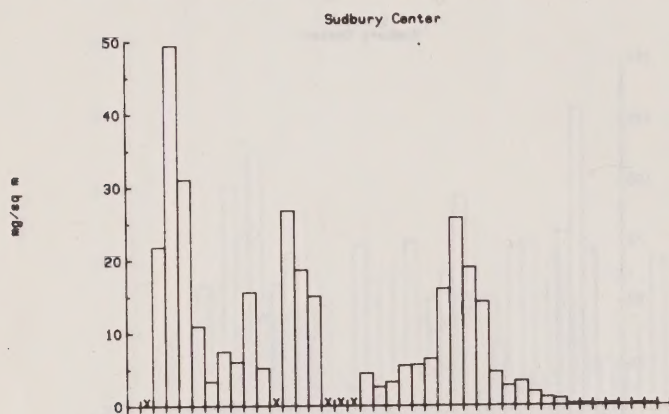
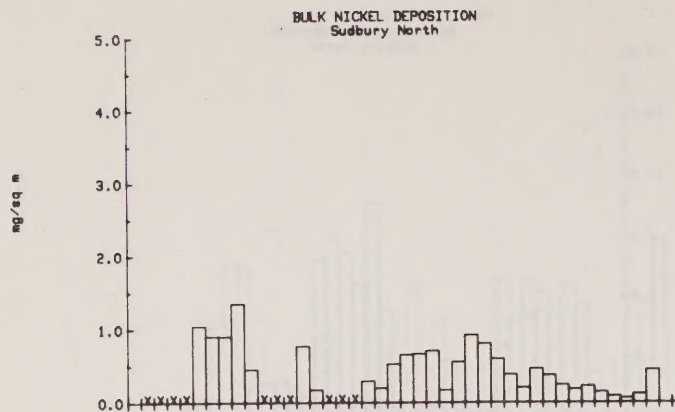
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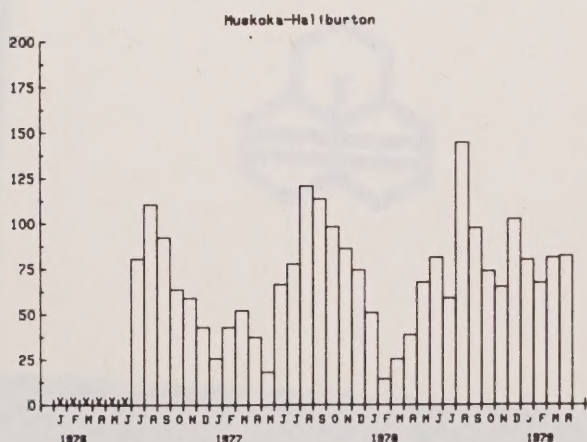
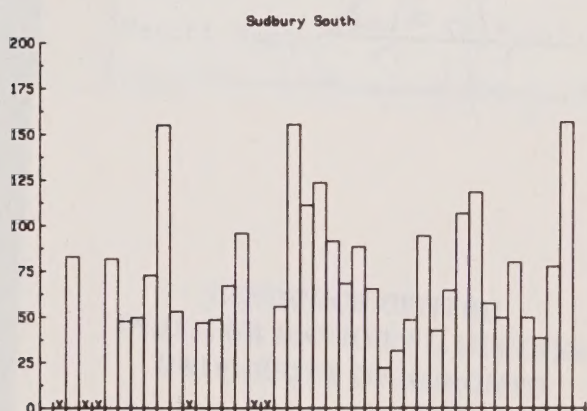
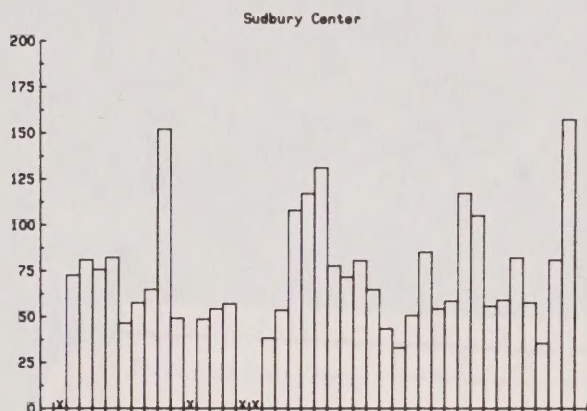
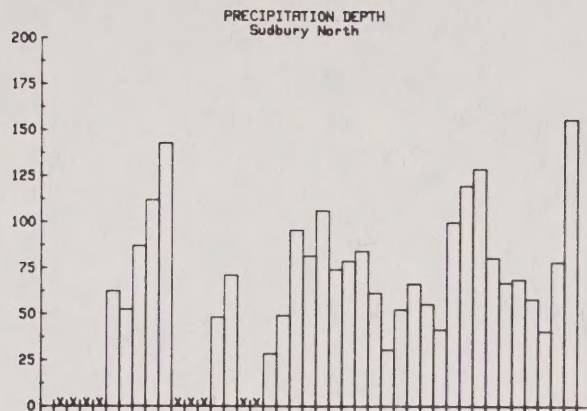


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